EFFICIENT FRAMEWORK FOR INTEGRATING DISTRIBUTED GENERATION AND CAPACITOR BANKS CONSIDERING SIMULTANEOUS GRID-CONNECTED AND ISLANDED DISTRIBUTION NETWORK OPERATIONS

ZOHAIB HUSSAIN LEGHARI

UNIVERSITI TEKNOLOGI MALAYSIA

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ZOHAIB HUSSAIN LEGHARI

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Faculty of Engineering
Universiti Teknologi Malaysia

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ABSTRACT

In literature, for the planning problem of simultaneous distributed generation (DG) and shunt capacitor banks (SCB) allocation in radial distribution networks (RDNs), researchers have focused mainly on the real power loss reduction and ignored the benefits of reactive power loss minimization, which might not distribute DGs and SCBs at the desirable locations. In addition, a variety of metaheuristic optimization techniques have been employed in literature whose implementation involves either the number of phases or tuning of certain algorithm-specific parameters. In contrast, the Jaya algorithm (JA) is a simple and efficient single-phase optimization algorithm that is free from any parameter tuning. However, the JA also suffers from inadequacies of population diversity and premature convergence; therefore, require a mechanism to overcome these deficiencies. Furthermore, past studies conducted for the islanded networks have followed the approach of isolated operation and did not consider the power supply-demand imbalance condition, which will result allocation of oversized DGs and SCBs. Considering these facts, this research work proposes a two-stage planning approach for the efficient utilization of DGs and SCBs for the simultaneous grid-connected and islanded operations of the RDNs. The first stage determines the optimal installation locations and capacities of DGs and SCBs, and operating power factor of DGs using an improved variant of the JA (IJaya) to minimize the total power loss and voltage deviation during the grid-connected operation. For the proposed IJaya, a dynamic weight parameter based grid-search mechanism has been introduced to mitigate the problem of premature convergence and population diversity in JA. The performance of the IJaya was evaluated using the IEEE 33-bus and 69-bus RDNs. A comparative analysis with existing optimization methods reveals that the IJaya achieves up to 38.84% more reduction in power losses and 3.26% more voltage improvement. In the later part of the study, a methodology concerning the efficient and maximum utilization of the installed DG-SCB capacity in the islanded RDN under power imbalance conditions has been proposed. For that, a multiobjective minimization function incorporating the total power loss and under-utilization of available DG-SCB capacity has been established. To minimize the proposed function, an iterative analytical approach has been proposed to tune the source power factor. The results showed that the under-utilization of available DG-SCB capacity varies up to 15.83% for the power factors ranging from 0.8 to 0.93. Expectedly, the proposed study will assist the utility companies to efficiently operate their distribution systems and to design effective energy management schemes for the customers.

ABSTRAK

Dalam literatur, untuk masalah perancangan penempatan serentak penjanaan teragih (DG) dan bank kapasitor pirau (SCB) dalam rangkaian agihan jejari (RDN), para penyelidik hanya memfokuskan pada pengurangan kehilangan kuasa sebenar dan mengabaikan faedah pengurangan kehilangan kuasa reaktif, yang mana ini mungkin akan menyebabkan pengagihan DG dan SCB tidak pada lokasi yang dikehendaki. Selain itu, perbagai teknik pengoptimuman metaheuristik telah digunakan dalam literatur yang pelaksanaannya melibatkan samada jumlah fasa atau penalaan parameter khusus algoritma tertentu. Sebaliknya, algoritma Jaya (JA) adalah algoritma pengoptimuman fasa tunggal yang mudah dan cekap yang bebas daripada sebarang penalaan parameter. Walau bagaimanapun, JA juga mengalami kekurangan kepelbagaian populasi dan penumpuan pramatang; oleh itu, memerlukan mekanisme untuk mengatasi kekurangan ini. Tambahan pula, kajian masa lalu yang dilakukan untuk rangkaian berpulau telah mengikuti pendekatan operasi terpencil dan tidak mempertimbangkan keadaan ketidakseimbangan bekalan kuasa-permintaan tenaga, yang mana akan menghasilkan penempatan DG dan SCB yang bersaiz lebih. Dengan mempertimbangkan fakta-fakta ini, kerja penyelidikan ini mencadangkan pendekatan perancangan dua peringkat untuk penggunaan DG dan SCB yang cekap untuk operasi RDNs yang terhubung dengan grid dan berpulau secara serentak. Tahap pertama adalah menentukan pemasangan lokasi dan muatan DG dan SCB yang optimum, dan faktor kuasa operasi DG menggunakan varian JA (IJaya) yang ditambahbaik untuk meminimumkan jumlah kehilangan kuasa dan penyimpangan voltan semasa operasi bersambung dengan grid. Untuk IJaya yang dicadangkan, parameter berat dinamik diperkenalkan untuk mengurangkan masalah penumpuan pramatang dengan mengekalkan kepelbagaian populasi dalam Jaya. Prestasi IJaya dinilai menggunakan IEEE 33-bas dan RDN 69-bas. Analisis perbandingan dengan kaedah pengoptimuman yang sediada menunjukkan bahawa IJaya mencapai pengurangan kehilangan kuasa sehingga 38.84% dan peningkatan voltan lebih dari 3.26%. Pada bahagian selanjutnya dari kajian ini, satu metodologi mengenai penggunaan yang cekap dan maksimum bagi muatan DG-SCB yang dipasang di RDN berpulau di bawah keadaan ketidakseimbangan kuasa dicadangkan. Untuk itu, fungsi pengurangan berbilang objektif yang merangkumi jumlah kehilangan kuasa dan kurang penggunaan muatan DG-SCB yang tersedia telah dihasilkan. Untuk meminimumkan fungsi yang dicadangkan, pendekatan beranalisis iteratif telah dicadangkan untuk menyesuaikan faktor kuasa sumber. Keputusan menunjukkan bahawa penggunaan yang kurang dari muatan DG-SCB yang tersedia berubah sehingga 15.83% untuk faktor kuasa antara 0.8 hingga 0.93. Dijangkakan, kajian yang dicadangkan akan membantu syarikat utiliti untuk mengendalikan sistem pengagihan mereka dengan cekap dan merancang skema pengurusan tenaga yang berkesan untuk pelanggannya.

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LIST OF ABBREVIATIONS

ABC	-	Artificial Bee Colony
AEO	-	Artificial Ecosystem Optimization
AGPSO	-	Autonomous Group Particle Swarm Optimization
AIS-ABC	-	Hybrid Artificial Immune System with Artificial Bee Colony
ALO	-	Ant-Lion Optimizer
ATC	-	Available Transfer Capability
BBO	-	Biogeography Based Optimization
BCAB	-	Binary Collective Animal Behaviour
BCBV	-	Branches Current to Bus Voltage
BFOA	-	Bacterial Foraging Optimization Algorithm
BF-PSO	-	Hybrid Bacterial Foraging and Particle Swarm Optimization
BFS	-	Backward-Forward Sweep
BGSA	-	Binary Gravitational Search Algorithm
BIBC	-	Bus Injection to Branch Current
BPSO	-	Binary Particle Swarm Optimization
BSA	-	Backtracking Search Algorithm
CAB	-	Collective Animal Behaviour
CSA	-	Cuckoo Search Algorithm
CSO	-	Cat Swarm Optimization
DE	-	Differential Evolution
DG	-	Distributed Generation
DICA	-	Discrete Imperialistic Competition Algorithm
DISCO	-	Distribution Company
DLF	-	Distributed Load Flow
DNO	-	Distribution Network Operator
DPSO	-	Discrete Particle Swarm Optimization
DSA	-	Direct Search Algorithm
DSM	-	Demand-Side Management
EGA	-	Enhanced Genetic Algorithm
EGWO-	-	Hybrid Enhanced Grey Wolf Optimizer with Particle Swarm

PSO		Optimization
ENS	-	Energy Not Supplied
ESGA	-	Elitist Speciation based Genetic Algorithm
EU	-	European Union
FFR	-	Feeder's Failure Rate
FGA	-	Fuzzy Genetic Algorithm
GA	-	Genetic Algorithm
GABC	-	G_{best} Guided Artificial Bee Colony
GMSA	-	Hybrid Genetic Algorithm and Moth Swarm Algorithm
GSA	-	Gravitational Search Algorithm
HSA	-	Heuristic Search Algorithm
HSA-PABC	-	Hybrid Harmony Search and Partial Artificial Bee Colony
ICA	-	Imperialistic Competition Algorithm
ICA-GA	-	Hybrid Imperialist Competitive Algorithm and Genetic Algorithm
ICSO	-	Improved Cat Swarm Optimization
IEEE	-	Institute of Electrical and Electronics Engineers
IGA	-	Improved Genetic Algorithm
IJaya	-	Improved Jaya Algorithm
IMDE	-	Intersect Mutation based Differential Evolution
IMPA	-	Improved Marine Predators Algorithm
IPP	-	Independent Power Producer
IPSO	-	Improved Particle Swarm Optimization
ITLBO	-	Improved Teaching Learning Based Optimization
IVM	-	Index Vector Method
JA	-	Jaya Algorithm
LLI	-	Line Loading Index
LR	-	Loss Reduction
LSF	-	Loss Sensitivity Factor
LW-IJaya	-	Linearly Decreasing Weight Parameter based Improved Jaya Algorithm
SCB	-	Shunt Capacitor Bank
MA	-	Memetic Algorithm

MG	-	Microgrid
MODE	-	Multi-Objective Differential Evolution
MOEA/D	-	Multi-Objective Evolutionary Algorithm based Decomposition
MOPSO	-	Multi-Objective Particle Swarm Optimization
MJA	-	Modified Jaya Algorithm
MPA	-	Marine Predators Algorithm
MSA	-	Modified Simulated Annealing
MSFLA	-	Modified Shuffled Frog Leaping Algorithm
MTLBO	-	Modified Teaching Learning Based Optimization
MVO	-	Multi-Verse Optimizer
NSGA	-	Non-dominated Sorting based Genetic Algorithm
OCSO	-	Opposition-based Competitive Swarm Optimizer
opf	-	Optimal power factor
OPF	-	Optimum Power Flow
PDF	-	Probability Distribution Function
PLI	-	Power Loss Index
PSO	-	Particle Swarm Optimization
PSO-OS	-	Particle Swarm Optimization with Orientation and Shrinking factor
PVDG	-	Photovoltaic Distributed Generation
SA	-	Simulated Annealing
SAIDI	-	System Average Interruption Duration Index
SAIFI	-	System Average Interruption Frequency Index
SFLA	-	Shuffled Frog Leaping Algorithm
SHO	-	Spotted Hyena Optimizer
SOS	-	Symbiotic Organisms Search
SPEA	-	Strength Pareto Evolutionary Algorithm
SSA	-	Salp Swarm Algorithm
SSA	-	Spring Search Algorithm
THD	-	Total Harmonic Distortion
TLBO	-	Teaching Learning Based Optimization
TLL	-	Total Line Loss
ToU	-	Time-of-Use

TPA	-	Thief and Police Algorithm
TS	-	Tabu Search
TS-CBGA	-	Hybrid Tabu Search and Chu–Beasly Genetic Algorithm
TVD	-	Total Voltage Deviation
upf		Unity power factor
VD	-	Voltage Deviation
VDI	-	Voltage Deviation Index
VR	-	Voltage Regulator
WCA	-	Water Cycle Algorithm
WDG	-	Wind-based Distributed Generation
WEG-IJaya	-	Improved Jaya algorithm based on evenly-spaced parameter bounds based grid-search mechanism
WIPSO	-	Weight-Improved Particle Swarm Optimization
WIPSO-GSA	-	Hybrid Weight Improved Particle Swarm Optimization and Gravitational Search Algorithm
WNN	-	Wavelet Neural Network
WRG-IJaya	-	Improved Jaya algorithm based on randomly-selected parameter bounds based grid-search mechanism

LIST OF SYMBOLS

$APEL$ - Annual active energy loss

$APEL_{base}$ - Annual active energy loss without DG-SCB

$APEL_{DG-SCB}$ - Annual active energy loss with DG-SCB

$APELR$ - Annual active energy loss reduction

$AQEL$ - Annual Reactive Energy Loss

$AQEL_{base}$ - Annual reactive energy loss without DG-SCB

$AQEL_{DG-SCB}$ - Annual reactive energy loss with DG-SCB

$AQELR$ - Annual reactive energy loss reduction

$ASEL$ - Annual Apparent Energy Loss

$ASEL_{base}$ - Annual apparent energy loss without DG-SCB

$ASEL_{DG-SCB}$ - Annual apparent energy loss with DG-SCB

$ASELR$ - Annual apparent energy loss reduction

br - Branch

$b1, b2$ - Buses $b1$ and $b2$

i - Candidate solution

I_{br} - Current flow through the branch

Itr/k - Iteration index

j - Decision variable

L_{DG} - Placement point (bus location) of a DG unit

L_{SCB} - Placement point (bus location) of a SCB unit

m - SCB unit number

$MaxItr$ - Maximum number of iterations

n - DG unit number

nb - Total number of buses in the distribution system

$nPop$ - Population size

$nVar$ - Number of Variables

N_{DG} - Total number of installed DG units

N_{SCB} - Total number of installed SCB units

$P_{available}$ - Sum of maximum real power outputs available from installed DG units

P_{br}	-	Real power supplied by branch at the sending-end bus
P'_{br}	-	Cumulative real power supplied by branch at receiving-end bus
$P_{br,loss}$	-	Real power loss occurred in branch
$P_{b2(F)}$	-	Real power flows to downstream branches connected at bus $b2$
$P_{b2(I)}$	-	Real power injected into the distribution system at bus $b2$
$P_{b2(L)}$	-	Real power consumed at bus $b2$
P_{DG}	-	Real power output of a DG unit
$P_{DG,max}$	-	Maximum real power generation capacity of a DG unit
$P_{generated}$	-	Sum of real power outputs generated by the mounted DG units during the islanded operation
P_{load}	-	Total real power demand of the distribution network
$P_{load,b}$	-	Total real power demand of bus b
P_{loss}	-	Active power loss
P_{loss_a}	-	Active power loss of the distribution network after integrating the DGs and SCBs
P_{loss_b}	-	Active power loss of the distribution network before integrating the DGs and SCBs
P_{lossT}	-	System's cumulative real power loss across the distribution network branches
$P_{0,b}$	-	Initial value of load's active power demand at bus b
P_{DG}^{total}	-	Total real power generation capacity of all DG units
pf_{DG}	-	Operating power factor of a DG unit
pf_{load}	-	Power factor of the distribution network's load
pf_{set}	-	Operating power factor of DG-SCB combination other than the pf_{source}
pf_{source} or pf_{DG-SCB}	-	Rated power factor of DGs and SCBs combination during the distribution networks' islanded operation
$\Delta P_b/\Delta P_{b+1}$	-	Change in active power demands of bus b and bus $b+1$
$Q_{available}$	-	Sum of maximum reactive power outputs available from installed DG and SCB units
Q_{br}	-	Reactive power supplied by branch at the sending-end bus

Q'_{br} - Cumulative reactive power supplied by branch at receiving-end bus

$Q_{br,loss}$ - Reactive power loss occurred in branch

$Q_{b2(F)}$ - Reactive power flows to downstream branches connected at bus $b2$

$Q_{b2(I)}$ - Reactive power injected into the distribution system at bus $b2$

$Q_{b2(L)}$ - Reactive power consumed at bus $b2$

Q_{DG} - Reactive power output of a DG unit

$Q_{DG,max}$ - Maximum reactive power generation capacity of a DG unit

$Q_{generated}$ - Sum of reactive power outputs generated by the mounted DG and SCB units during the islanded operation

Q_{load} - Total reactive power demand of the distribution network

$Q_{load,b}$ - Total reactive power demand of bus b

Q_{lossT} - System's cumulative reactive power loss across the distribution network branches

Q_{max} - Maximum capacity/size of SCB units

Q_{SCB} - Reactive power output of a SCB unit OR SCB size

$Q_{SCB,max}$ - Maximum reactive power generation capacity of a SCB unit

Q_o - Standard size/capacity of single SCB unit

$Q_{0,b}$ - Initial value of load's reactive power demand at bus b

$Q_{DG/SCB}^{total}$ - Total reactive power generation capacity of all DG and SCB units

Q_{SCB}^{min} - Minimum power generation bound for a SCB unit

Q_{SCB}^{max} - Maximum power generation bound for a SCB unit

$\Delta Q_b/\Delta Q_{b+1}$ - Change in reactive power demands of bus b and bus $b+1$

R_{br} - Resistance of the branch

$r_{1,j}^k, r_{2,j}^k$ - Random numbers for j^{th} decision variable in k^{th} iteration

$rand(0,1)$ - Random number between 0 and 1

$S_{available}$ - Total installed capacity of the DG and SCB units

S_{br} - Total power supplied by branch at the sending-end bus

S_{DG} - Size of DG unit/Apparent power output of DG unit

$S_{generated}$ - Total power generated by the installed DG and SCB units during the islanded operation

S_{load} - Total (apparent) power demand of the distribution network

$S_{under-utilization}$ - Under-utilization of the installed power generation capacity

S_{DG}^{min} - Minimum power capacity (size) bound for a DG unit

S_{DG}^{max} - Maximum power capacity (size) bound for a DG unit

T - Time in hours from 1 to 24

T_{loss_a} - Total power loss of the distribution network after integrating the DGs and SCBs

T_{loss_b} - Total power loss of the distribution network before integrating the DGs and SCBs

T_{lossT} - Total (apparent) power loss across the entire distribution system

VD - Voltage Deviation

VD_b - Voltage Deviation at bus b

VDI - Voltage Deviation Index

VDI_a - Voltage Deviation Index of the distribution network after integrating the DGs and SCBs

VDI_b - Voltage Deviation Index of the distribution network before integrating the DGs and SCBs

V_b - Voltage measured at bus b

V_{b1}, V_{b2} - Voltage magnitude at buses $b1$ and $b2$

V_{min_a} - Minimum bus voltage of the distribution network after integrating the DGs and SCBs

V_{min_b} - Minimum bus voltage of the distribution network before integrating the DGs and SCBs

V_{rated} - Rated (base) voltage of the distribution network

U - An integer multiple

ω - Linearly decreasing weight parameter

ω_{ub} - Upper bound of the weight parameter

ω_{lb} - Lower bound of the weight parameter

X_{br} - Reactance of the branch

$z_{min,j}$ - Minimum bound for the j^{th} decision variable

$z_{max,j}$ - Maximum bound for the j^{th} decision variable

z_{best}^{k}	-	best candidate solution for k^{th} iteration
$z_{i,j}^{k}$	-	Current solution of j^{th} decision variable, i^{th} candidate in k^{th} iteration
z_{worst}^{k}	-	worst candidate solution for k^{th} iteration
$Z_{i,j}^{k}$	-	Updated solution of j^{th} decision variable, i^{th} candidate in k^{th} iteration
θ	-	Power factor angle of DG unit
α	-	Weight Factor

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CHAPTER 1

INTRODUCTION

1.1 Background

Ever since the first electrical power system was created, there is a continuous expansion in this most complex human-made system. The easy controlling, adaptable, and dispatchable nature of electrical energy are some of the fascinating reasons for its constantly increasing growth in demand [1]. According to the international energy outlook report 2016 [2], the worldwide net electricity demand was 22 trillion kWh in 2012, rising by 1.9% per year on average from 2012 to 2040. This rapid increase in load demand has resulted in a bottleneck in the transmission system [3]. Therefore, electric utilities face unavoidable issues, including increased line losses, deteriorating voltage profile, increase in generation cost, reduction in the electric grid's reliability, and general security issues. The possible solution to meet the increasing electricity demand is installing conventional fuel-based large power plants and replacing existing or integrating new transmission lines. However, these solutions are not recommended due to high investment costs and severe environmental concerns [4].

As an alternative solution for centralized power generation, the optimal integration of distributed generation (DG) in the distribution networks has attracted the attention of the energy planners and policymakers due to their unavoidable technical, environmental, and economic benefits [5]. The International Energy Agency (IEA) defines DG as an electricity source connected directly to the distribution network to serve a local customer and provide support to the network [6]. DGs can either be based on renewable or non-renewable source [7]. In the case of a passive distribution network (i.e., without DG integration), the distribution network's total power demand is solely supported by the grid located far away from the load center. As a result, when the load demand rises, the power losses also increase due to the current increase. On the other side, by locating DGs close to the load points, some of the loads' required power is supplied by the DGs, reducing the primary grid's transmitted power. This causes a considerable decrease in power losses. Besides, because of the DG's presence, the distribution network does not depend entirely only on a single power resource (i.e., electric substation) to fulfill the load demand, enhancing the distribution network's reliability. The installation of DGs in the power distribution networks has several other advantages: such as improvement in bus voltage profiles, power quality enhancement, and deferment in construction of new power plants, transmission and distribution lines [8]. Apart from that, DGs' existence in the distribution networks also enables the utility to utilize them as a backup solution. Thus, in case of eventualities giving the islanding capabilities offered by decentralized power generation units. Even if the DGs' installed capacity is lower than the network's connected load, at times of energy deficiency, the distribution network operators (DNOs) will supply the available power to a specific zone consists of the critical load in the distribution network. The DNOs could also influence the consumers to limit their electricity usage so that the installed DGs can supply at least a fraction of each consumer's load demand with available energy. Hence, in a context of increased uncertainty in electricity demand and supply, DGs present the advantage of being installed with lower risk and change in the existing infrastructure, transforming power systems from centralized to decentralized networks [9].

On the other hand, shunt capacitor banks (SCBs) are the devices that have always been regarded as the most economical solution for power loss reduction and volt/var control of the distribution systems [10]. Capacitors are amongst the first pieces of equipment used to improve the power system voltage [11]. Although DGs alone offer better performance than SCBs [12] in the prospect of power losses and voltage regularity, however, the investment cost of DGs is very high compared to SCBs. The related control, protection, and interface components for the DGs further add to the capital cost. As an estimate, the capital cost of 1MW diesel generator-based DG is 50 times greater than the SCB of 1 MVAR rating [12]. Therefore, considering modern distribution systems, DGs and SCBs coexist, and they share some of their operational tasks. Thus, to maximize the techno-economic benefits, DGs and SCBs must be simultaneously allocated to distribution networks. However, it is a well-known fact that among three components of the power system, the distribution system has the highest power losses due to the higher line resistance (R) to reactance (X) ratio, lower voltage levels, and radial configuration [13]. As per the states, the distribution system accounts for almost 70% of the total power system losses [14]. Whereas the reference [15] has shown this range from 33.7% to 64.9%. In these circumstances, let's ensure that the DG's and SCB's outputs must be optimized before integrating them into the distribution networks to maximize their benefits. Without the optimal DG and SCB outputs, they might cause higher power loss and voltage deterioration in the distribution network than the initial condition when no DG or SCB is connected. Hence, an appropriate planning methodology must be carried out to incorporate DG and SCB units into the distribution network to get constructive benefits for grid-connected and autonomous operations.

Therefore, this research's focus is to propose a technique that can find an optimal siting and sizing of DG and SCB units to achieve better performance of the grid-connected distribution network. Furthermore, this research work proposes a framework to maximize the utilization of the mounted DG and SCB units under the islanded operation of the distribution network for the scenario where the power supply is less than the power demand. The research questions highlighted while analyzing the impacts of DG and SCBs for both non-autonomous and autonomous operations of the distribution network are given below:

i. Which suitable method can be used to determine the optimal size and placement of DG and SCB units?
ii. What will be the effect of optimal siting and sizing of DG and SCB units on the power/energy loss and voltage deviation in the distribution system?
iii. What will be the impact of optimizing the operating power factor of DGs on the performance of grid-integrated distribution networks?
iv. How can the installed DG and SCB units be utilized to their full capacities under the islanded operation of the distribution network so that the maximum share of the total network load can be supplied with accessible power?
v. What will be the effect of the operating power factor of the DG and SCB combination on the power loss and utilization of the installed DG-SCB capacity under the islanded operation of the distribution network?

All the listed problems will be analyzed and discussed in detail in this study.

1.2 Problem Statement

i. For the planning problem of simultaneous DG and SCB allocation in radial distribution networks (RDNs), researchers have focused mainly on the real power loss reduction and ignored the benefits of reactive power loss minimization. Targeting merely the real power loss minimization in the objective function might not distribute DG and SCB units at the most desirable sites since the objective may fail to pinpoint places in the network where reactive power is dominating. The fact that there are unknown line-segments with a lot of reactive power flow makes it difficult to choose the ideal rating and position for the SCB. Knowing that reactive power flow causes real power loss and voltage drop in the RDNs, not addressing reactive power flow minimization with improper placement and sizing of the SCB directly affects the DG's rating and location in the network. Therefore, focusing on minimizing net reactive power flow is equally critical, and if a multiobjective function is developed to address both power components, system performance could be improved even more.

ii. In literature, simultaneous DG and SCB allocation optimization problems in the RDNs, a variety of metaheuristic optimization techniques has been employed whose implementation involves either the number of phases or the tuning of certain algorithm-specific parameters. To enhance such algorithms' performance and obtain a global solution, researchers must tune the special parameters properly; else, the performance of the algorithm will be affected. In contrast, the Jaya algorithm (JA) developed by R. Rao [16] involves a single step only and does not require algorithm-specified parameters. In contemporary literature [17–26], the JA has proved its dominant performance over various optimization algorithms applied in numerous fields. However, the JA also suffers from the deficiency that it does not take full advantage of population data. The JA learning approach uses the current best solution and the current worst solution to guide the population's search direction. As a result, once the current best individual has been stuck in local optimum, additional individuals will be drawn to approach this local optimum gradually. Hence, the population diversity will be lost as a result of this case [27]. Therefore, before deploying JA to solve the optimization problem of simultaneous DG and SCB allocation into the distribution networks, it is imperative to propose a mechanism for improving the JA's performance.

iii. The presence of DGs-SCBs allow the RDN to operate as a microgrid (MG) in the times when the power grid faces malfunctioning, brief shortage of energy or is being maintained. To the best of author’s knowledge and literature presented in this thesis, so far only three studies [28–30] extracts this vital feature of MG formation while allocating the DGs and SCBs in the RDNs. Furthermore, while optimally allocating the DGs alone, a methodology for the optimal siting and sizing of DG units in an autonomous MG has been reported in very few studies [31–33]. However, in contemporary literature, the approach of isolated operation has been adopted for the islanded networks while the power supply-demand disparity situation has not been addressed. Remember that, although islanded and isolated MGs have almost equivalent control and operational requirements, they are different from a planning point of view due to the short time of MG operation in the islanded mode [34]. Installing larger-sized DGs to meet the energy demand of complete load for this short duration can assure the islanded grid's sustainable operation. However, it will increase the power system's overall cost and make the electric grid more complex. Therefore, instead of allocating the oversized DGs and SCBs, there siting and sizing must be determined considering the grid-connected mode they have to serve for most of their service life. Furthermore, it is imperative to develop a mechanism to efficiently operate the installed same devices to their full potential during the islanded operation in order to serve the maximum possible share of total network load under supply-demand imbalance conditions.

iv. In a RDN, once the DGs and SCBs are installed considering its grid-connected operation, it is not easy to alter their sizes and bus positions during islanded mode. Therefore, a mechanism must be developed to tune their outputs, without affecting DGs-SCBs sizes and locations, in order to efficiently operate the islanded networks and serve the maximum possible share of total network load under supply-demand imbalance conditions. The development of such mechanism allows minimizing degree of difference between the energy supply and demand, Figure 1.1. The smaller the supply and demand gap, the easier will be the designing of energy management schemes for MGs.

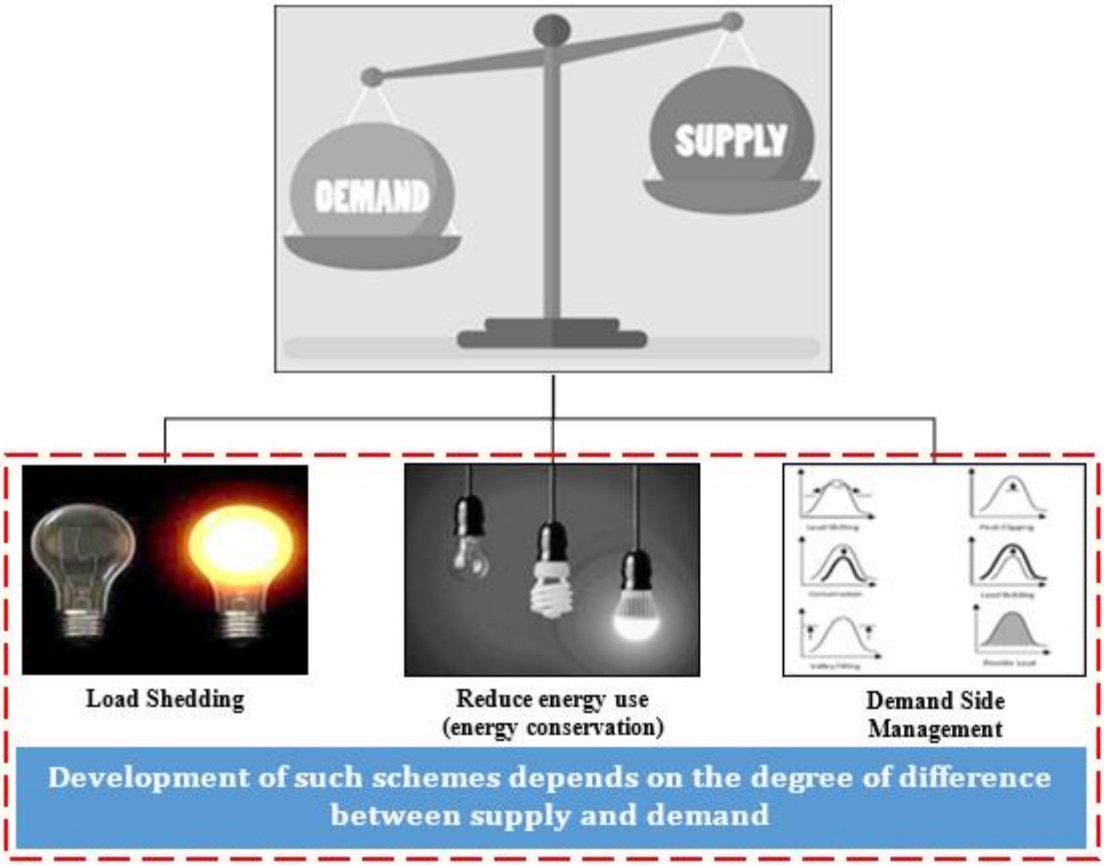

Figure 1.1 Strategies to deal with the supply-demand imbalance (when, $P_{demand} \geq P_{supply}$)

1.3 Research Objectives

In view of the problems highlighted above, the objectives of this research work are as follows:

i. To develop a multi-criterion minimization function incorporating the active power loss, reactive power loss, and voltage deviation to optimize the grid-connected radial distribution networks' functioning.

ii. To develop an improved variant of JA (IJaya) to minimize the developed multi-criterion function by optimizing the siting and sizing of DG and SCB units, as well as the power factor of DG units in the distribution networks.

iii. To develop a multi-criterion minimization function incorporating the total power loss (active and reactive) and under-utilization of the available DG-SCB capacity to optimize the islanded distribution networks' functioning.

iv. To develop an analytical framework correlating the efficient and maximum utilization of the DG and SCB capacities in the autonomous operation mode under the power supply-demand imbalance condition.

1.4 Research Scope

The scopes of this research work summarized as follow:

i. The present study considers only the steady-state conditions; thus, transient analysis has not been conducted.

ii. The technical constraints of the distribution system, such as bus voltage limit, power flow limits, DG's and SCB's size, and location constraints, are considered. However, control and protection attributes are not studied.

iii. Economic and environmental study of the presented methodology is not carried out because further studies are required in the direction of these research topics.

iv. The proposed research work has been evaluated using the IEEE 33-bus and 69-bus test systems whose specifications were taken from the literature.

v. The maximum number for each DG and SCB unit permissible to allocate in each test system is three because the percentage improvement in system performance is negligible with more units.

vi. DGs and SCBs are considered in the forms with deterministic active and reactive power outputs, respectively. Hence, the intermittency in DG's and SCB's outputs is not considered.

vii. The development of load shedding and energy management schemes is beyond the scope of this research.

1.5 Significance of the Research

Compared to the transmission system, the distribution network is a more complex system due to the high R/X ratio and higher power losses in the electrical power system. Reduction of such power loss is of severe concern for distribution companies (DISCOs). Integration of DG and SCB units and network reconfiguration are significant standpoints for power loss reduction. For this reason, simultaneous DG and SCB placements in the distribution networks have become a renowned research area in the last few years. If appropriately positioned with optimum size, the simultaneous incorporation of both DG and SCB units in the distribution networks can play a vital role in reducing the power losses and improving the voltage level considerably.

In the last few years, the researchers have utilized various metaheuristic-based techniques to solve the complex combinatorial optimization problem of simultaneous DG and SCB allocation. The past studies have made valued contributions by improving the optimization algorithms in solving the planning problem of optimal siting and sizing of DG and SCB units in the distribution networks. Developing a suitable metaheuristic algorithm for the DG-SCB allocation-planning problem is vital. Since a minor improvement in the metaheuristic algorithms would significantly positively affect the distribution networks' performance. This reason has inspired the author to develop an improved optimization algorithm and compare it with existing methods employed for the distribution networks' planning problem of simultaneous DG-SCB allocation. The no-free-lunch theorem [35] also states that no metaheuristic algorithm is specifically best for all types of optimization problems, thus emphasizing the need for comparisons and the development of new optimization approaches.

Conversely, one of the vital aspects of DG integration into the distribution networks is that the DGs presence will allow an MG to establish when the primary grid faces fault or is under maintenance. This is one of the critical features of the DG integration into the distribution networks, which has not been explored extensively. During the grid-connected operation of the distribution networks, the active power and reactive powers of DG and SCB units can be dispatched according to techno-economic criteria conducted at the main grid. Thus, in grid-connected mode, the DG-SCB integration's principal task minimizes the distribution network's power losses and voltage regulation. Whereas, during the islanded operation, the distribution network operates as an MG. This independent entity is solely responsible for maintaining the real and reactive power balance between supply and demand. If the net load demand is less than the total generation, the MG's central controller should decrease the net power generation.

On the other hand, if the power generation within the MG is insufficient to meet the load demand, either the load shedding of the non-critical or activation of a demand-side management scheme (DSM) must be considered. While analyzing the performance of the distribution networks as an MG, past studies have mainly focused on the frequency control and voltage stability of the developed MGs. However, existing studies did not address the concern of utilizing the installed DG-SCB capacity to their full potential such that the maximum possible share of total network load can be served when the power demand exceeds supply. Therefore, it necessitates the development of a mechanism to resolve the issue posed. It will help utilities design effective load shedding and energy management schemes for their customers to make the autonomous networks more reliable. Such a methodology would also allow the utilities to deliver the same load with the lowest possible installed active-reactive power generation.

1.6 Thesis Organization

This thesis is divided into five chapters. The rest of the thesis is organized as follows:

Chapter 2 presents the comprehensive review for the optimal planning of simultaneous allocation of DG and SCB units in the distribution networks. This chapter highlights the state-of-the-art optimization techniques, research objectives, constraints, decision variables, operation modes, and load types of the distribution networks, which are the solid basis for this research work. The problem statement and research objectives, as stated in Chapter 1, are derived from this chapter.

Chapter 3 provides the detailed formulation of the optimization problems and implementation of the proposed methodologies adopted to optimize the functioning of the distribution networks under both non-autonomous and autonomous operation modes. In the first part of the chapter, to solve the planning problem of simultaneous DG and SCB allocation in the grid-connected distribution network, an improved variant of the Jaya algorithm has been proposed. The developed problem formulation comprises bi-objectives that include minimizing total power loss (active and reactive power losses) and voltage deviation at the nodes, which are dealt with ε-constraint and weighted-sum-based multiobjective optimization approaches. In the later part of the chapter, an analytical method has been proposed to solve the planning problem of efficient and maximum utilization of the mounted DGs and SCBs to their full potential during the network's autonomous operation under supply-demand imbalance conditions. For that, a weighted-sum-based multi-criterion minimization function incorporating the total (apparent) power loss and under-utilization of available DG-SCB capacity has been developed.

Chapter 4 presents the outcomes of this research investigation. Similar to Chapter 3, Chapter 4 is also divided into two parts. The former part of the chapter discusses the results obtained for the standard benchmark functions, and the grid-connected IEEE 33-bus and 69-bus test systems. The islanded 33-bus and 69-bus distribution networks are discussed in the latter part of this chapter.

Chapter 5 summarizes the findings and contributions of the research work. Moreover, this chapter also provides recommendations for future research directions.

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LIST OF PUBLICATIONS

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2. **Leghari, Z. H.**, Hassan, M. Y., Said, D. M., Memon, Z. A., and Ansari, S. An efficient framework for integrating distributed generation and capacitor units for simultaneous grid-connected and islanded network operations. *International Journal of Energy Research*. 2021: 1-39. https://doi.org/10.1002/er.6768. **(Published, Q1, IF: 5.164)**